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***In vitro* activity of 2,4-diamino-6-[2-(phosphonomethoxy)ethoxy]-pyrimidine against multidrug-resistant hepatitis B virus (HBV) mutants**

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**Running title:** PMEO-DAPym cross-resistance profile on HBV replication

## ABSTRACT

The susceptibility of drug-resistant hepatitis B virus (HBV) mutants to lamivudine, adefovir, tenofovir, entecavir and 2,4-diamino-6-[2-(phosphonomethoxyethoxy)pyrimidine (PMEO-DAPym), a novel acyclic pyrimidine analogue, was assessed *in vitro*. Most drug-resistant mutants, including multidrug resistant strains, remained sensitive to tenofovir and PMEO-DAPym. Therefore, the latter molecule deserves further evaluation for the treatment of HBV infection.

1 Treatment of chronic hepatitis B virus (HBV) infection requires long term administration with  
 2 nucleos(t)ide analogs [lamivudine [(-)-β-L-2',3'-dideoxy-3' thiacytidine]], adefovir dipivoxil  
 3 (9-[(2-phosphonylmethoxy)ethyl]adenine), entecavir (2-amino-1,9-dihydro-9-[(1*S*, 3*R*, 4*S*)-4-  
 4 hydroxy-3-(hydroxymethyl)-2-methylenecyclopentyl]-6*H*-purin-6-one, monohydrate) or  
 5 telbivudine (β-L-2'-deoxythymidine)] (28). However, this leads to the emergence of HBV  
 6 strains harbouring mutations within the reverse transcriptase (RT) sequence that confer  
 7 resistance to these drugs (14, 28, 29). The incidence of resistance increases progressively each  
 8 year, reaching 70 % after 4 years of lamivudine and 29% after 5 years of adefovir dipivoxil  
 9 therapy (9, 14). Currently, there are two options to treat patients who carry lamivudine-  
 10 resistant mutants. Lamivudine can be switched to adefovir-dipivoxil or entecavir with the risk,  
 11 however, of developing adefovir-resistance (7, 8) or entecavir-resistance (4, 19) in the long-  
 12 term. Adefovir dipivoxil can also be added to ongoing lamivudine monotherapy (7, 8) to  
 13 delay further resistance, as both drugs have a favorable cross-resistance profile when used in  
 14 combination (1, 22, 29). However, the emergence of HBV strains harbouring simultaneously  
 15 lamivudine- and adefovir-resistance mutations was recently reported within the viral  
 16 quasispecies of a patient who successively failed lamivudine and lamivudine plus adefovir  
 17 dipivoxil add-on therapy (24). The HBV resistant mutants that are selected after successive  
 18 failure to lamivudine and entecavir are resistant to both drugs (20, 23, 26). Thus, the  
 19 development of novel HBV inhibitors is needed to overcome HBV drug resistance, and to  
 20 design new combination strategies to delay or prevent drug resistance. Different nucleoside  
 21 analogs are currently in development. Recently, 2,4-diamino-6-[(2-  
 22 phosphonmethoxy)ethoxy]pyrimidine (PMEO-DAPym), an acyclic pyrimidine nucleoside  
 23 analog phosphonate, was shown to inhibit *in vitro* human immunodeficiency virus (HIV) and  
 24 HBV replication with a potency comparable to that of adefovir and tenofovir [(*R*)-9-[(2-  
 25 phosphonylmethoxy)propyl]adenine] (2, 11, 27). Tenofovir has been approved for HIV

therapy and is in phase III trial for HBV infection (25). Moreover, PMEO-DAPym proved to have equipotent activity against wild-type (wt) and lamivudine-resistant rtM204V mutant HBV in inducible transfected hepatoma cell lines (27). In the present study, we investigated, in transiently transfected Huh7 cells, the cross-resistance profiles of a series of drug-resistant HBV mutants, including multiple drug-resistant strains, to PMEO-DAPym and this in direct comparison with other drugs in parallel assays.

First, we determined the effect of the compounds on Huh7 cell viability by determining the concentration of drug that reduced the uptake of neutral red dye by 50 % (CC<sub>50</sub>), as described before (10). Transient transfection of Huh7 cells was then performed as previously described with plasmids containing 1.1 genome unit of wt or mutant HBV strain under the control of the chicken beta actin promoter (6). One group of constructs contained the genome of HBV laboratory strains (genotype D, serotype ayw) including wt and resistant HBV mutants obtained by site directed mutagenesis (lamivudine-resistant: rtL180M/M204V; adefovir-resistant: rtN236T; lamivudine+adefovir-resistant: rtL180M/M204V/N236T) (3, 6, 17). The second group of constructs contained HBV genomes cloned from the viral quasiespecies of two HBV chronically infected patients who failed sequential therapy with currently approved HBV inhibitors (23, 24). The following clinical isolates (cloned HBV genomes) were studied: lamivudine-resistant mutants: rtL180M/M204V, rtL180M/A181V, rtV173L/L180M/M204V; lamivudine+adefovir-resistant mutants: rtV173L/L180M/A181V, rtV173L/L180M/A181V/M204V, rtV173L/L180M/A181V/M204V/N236T, rtV173L/L180M/A181V/N236T; entecavir-resistant mutant: rtL180M/S202G/M204V. Antiviral assays using transfected cells, purification of intracellular HBV DNA and its analysis by southern blotting were performed as previously described (3, 6).

As shown in Table 1, in Huh7 cells, PMEO-DAPym had little or no effect on cell viability [CC<sub>50</sub> > 1,000  $\mu$ M], as was also the case for lamivudine and tenofovir. The CC<sub>50</sub>

1 value for entecavir and adefovir were  $125 \pm 35 \mu\text{M}$  and  $365 \pm 120 \mu\text{M}$ , respectively.  
 2 Furthermore, PMEO-DAPym had no effect on HBsAg production by WT HBV transfected  
 3 cells (data not shown). When the anti-HBV activity was assessed, entecavir proved to be the  
 4 most potent compound with the lowest 50% effective concentration ( $\text{EC}_{50}$ ), followed by  
 5 lamivudine, PMEO-DAPym, adefovir and tenofovir. The  $\text{EC}_{50}$  of PMEO-DAPym was 3 to 4-  
 6 fold lower than that of adefovir and tenofovir, under our *in vitro* conditions (Table 1). The  
 7  $\text{EC}_{50}$  of PMEO-DAPym was higher under our *in vitro* conditions using Huh7 cells by  
 8 comparison with the results obtained in a stable cell line derived from HepG2 cells (27). This  
 9 type of  $\text{EC}_{50}$  variations between Huh7 and HepG2 cells has already been observed previously  
 10 with other nucleoside analogs (17); however the ranking of antiviral potency was not affected.  
 11 This may indicate that the intracellular metabolism including entry, transport,  
 12 phosphorylation, and pumping out of this nucleoside analogs may depend on the cell lines  
 13 used for the experiment.

14 PMEO-DAPym inhibited the replication of both laboratory and clinical lamivudine-  
 15 resistant HBV variants, rtL180M/M204V and rtV173L/L180M/M204V strains, as efficiently  
 16 as wt HBV (Tables 2, 3). The rtL180M/A181V mutant displayed a 4.8-fold decreased  
 17 susceptibility to PMEO-DAPym. However, among the drugs studied, tenofovir was the only  
 18 one which inhibited this mutant as well as wt HBV (Table 3). Lamivudine-resistant HBV  
 19 strains show decreased susceptibility to entecavir as compared with wild-type HBV strains  
 20 (Tables 2, 3). Interestingly, the laboratory HBV strain rtL180M/M204V engineered by site  
 21 directed mutagenesis (Table 2) is more susceptible to entecavir than its counterpart derived  
 22 from one patient (Table 3). Discrepancies between the susceptibility to entecavir of  
 23 laboratory- or patient- derived HBV rtL180M/M204V strains were already observed (20), and  
 24 may be explained by differences in the genetic background of the strains outside of the  
 25 polymerase region that has been cloned.

As previously reported, the rtN236T mutation identified in patients who failed adefovir dipivoxil therapy decreased the sensitivity to adefovir by 3.2 to 7.3 (1, 3, 22) and to tenofovir by 4.5-fold (3) (Table 2). The rtL180M/S202G/M204V mutant, identified in a patient who failed successively lamivudine and entecavir therapy (23), displayed a 210-fold resistance to entecavir and a >100-fold resistance to lamivudine (Table 3). Interestingly, both adefovir- and entecavir-resistant HBV strains were sensitive to PMEO-DAPym (Tables 2, 3)

All four lamivudine+adefovir-resistant mutants, characterized in a patient who failed sequential therapy, displayed a 2.1 to 5.1-fold decreased susceptibility to PMEO-DAPym depending on the combination of mutations they harboured (Table 3). The  $EC_{50}$  of PMEO-DAPym for mutants rtV173L/L180M/A181V, rtV173L/L180M/A181V/M204V and rtV173L/L180M/A181V/M204V/N236T was lower than that of tenofovir and similar for mutant rtV173L/L180M/A181V/N236T. However, the resistance factor observed for all four lamivudine+adefovir-resistant mutants was slightly higher for PMEO-DAPym as compared to tenofovir. PMEO-DAPym and tenofovir had a greater inhibitory activity on these multiple drug-resistant mutants than lamivudine and entecavir; adefovir had slightly higher resistance factors for these mutants but its *in vivo* pharmacological characteristics preclude its use at higher dosage (15). The inhibitory activity of the evaluated compounds against the rtV173L/L180M/A181V/N236T mutant (lamivudine and adefovir escape mutant) was ranged in the following order of potency: tenofovir > PMEO-DAPym > entecavir > adefovir > lamivudine.

Our results provide direct information regarding the cross-resistance profile of the lamivudine-, lamivudine+adefovir- and entecavir-resistant HBV strains isolated from patients who failed sequential therapy. Noteworthy, entecavir may not represent the best anti-HBV agent to treat patients who failed a lamivudine therapy, as lamivudine may lead to the emergence of HBV variants harbouring rtL180M/M204V or rtL180M/A181V mutations that

1 impair the antiviral effect of entecavir (Tables 2 and 3). Moreover, long-term entecavir  
 2 treatment of patients infected with lamivudine resistant HBV strains leads to the selection of  
 3 secondary mutations that, on a genetic background of lamivudine-resistant mutations, confer  
 4 increased resistance to entecavir (20, 23). Nevertheless, entecavir may be valuable for the  
 5 treatment of patients who failed adefovir dipivoxil therapy since mutants harbouring the  
 6 rtN236T mutation, in absence of the lamivudine-resistant mutation rtM204V, retained  
 7 susceptibility to entecavir (Tables 2 and 3) (3). Tenofovir displayed an antiviral activity  
 8 against wt HBV similar to adefovir (Table 1), and efficiently inhibited the replication of a  
 9 series of lamivudine-, adefovir-, lamivudine+adefovir- and entecavir-resistant HBV strains  
 10 (Tables 2 and 3). Clinically, tenofovir has been used successfully for the treatment of patients  
 11 who successively failed lamivudine and lamivudine+adefovir dipivoxil therapy (16, 23, 24).  
 12 Several clinical reports suggested a potent anti-HBV activity of tenofovir in patients failing  
 13 adefovir therapy and moreover a better anti-HBV activity of tenofovir over adefovir in  
 14 patients failing lamivudine therapy (13, 21), which may be due to better pharmacokinetic  
 15 properties. Whether tenofovir may select for drug-resistant mutants in patients remains a  
 16 matter of controversy (5, 18).

17 The development of novel strategies for HBV therapy that may be based on the  
 18 combination of various nucleoside analogs with different cross-resistant profile will require  
 19 the discovery of novel HBV inhibitors. We recently demonstrated the *in vitro* potency of the  
 20 2', 3'-dideoxy-3'-fluoroguanosine to inhibit wt, lamivudine-, adefovir- and lamivudine +  
 21 adefovir-resistant laboratory HBV strains (12). In the present study, we confirmed previous  
 22 studies that showed that PMEODAPym is a potent inhibitor of wt HBV *in vitro* (27).  
 23 Interestingly, we provide new information showing that PMEODAPym inhibits the  
 24 replication of lamivudine-, entecavir-, adefovir- and lamivudine+adefovir-resistant mutants  
 25 almost as efficiently as that of wt HBV (Tables 2 and 3). The *in vitro* cross-resistance profile



of PMEO-DAPym on the laboratory and clinical strains studied here proved to be more favorable than that of lamivudine, adefovir and entecavir, and was more or less comparable to that of tenofovir.

Interestingly, PMEO-DAPym efficiently inhibited all HBV variants harbouring the rtL180M/M204V mutations which is the most frequently observed lamivudine-resistant mutant in patients (14, 30) (Tables 2 and 3). Until now, only purine analogs, such as adefovir or tenofovir, have shown activity against the replication of the lamivudine-resistant rtL180M/M204V mutant which is resistant to lamivudine and all known pyrimidine L-nucleosides (29). Thus, PMEO-DAPym, although not carrying a purine base, exhibits the same cross-resistance profile as purine-based nucleoside phosphonate analogs. This supports our earlier assumption that (based on molecular modelling) that the 2,4-diamino-substituted pyrimidine ring of PMEO-DAPym can be viewed as a open-ring analog of the purine system in the 2,6-diaminopurine acyclic nucleoside phosphonate derivatives (27). Although most adefovir- and lamivudine+adefovir-resistant HBV strains retained some degree of susceptibility to adefovir *in vitro* (Table 2 and 3), its clinical efficacy is limited by its nephrotoxicity when the daily dose of adefovir dipivoxil is increased from 10 to 30 mg (15). In our experimental conditions, tenofovir and PMEO-DAPym exhibited the most favourable *in vitro* cross-resistance profiles as inhibitors of the replication of multiple drug-resistant HBV genomes derived from clinical strains from patients who failed sequential therapy with currently approved HBV inhibitors. Therefore, it will be interesting to determine the pharmacodynamics of PMEO-DAPym *in vivo*.

In conclusion, the broad inhibitory activity of PMEO-DAPym against HBV drug-resistant mutants and its favorable cytotoxicity profile, observed in tissue culture experiments, warrants further pre-clinical evaluation of this compound in animal models of hepadnavirus infection.

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## Tables

**Table 1: Activity of PMEO-DAPym and selected compounds against wild-type HBV replication and cell viability in Huh7 cells.**

Compound	EC <sub>50</sub> (μM) <sup>1</sup>	CC <sub>50</sub> (μM) <sup>2</sup>
Lamivudine	1 ± 1.1	> 1000
Entecavir	0.3 ± 0.42	125 ± 35
Adefovir	13 ± 29	365 ± 120
Tenofovir	16 ± 7.9	> 1000
PMEO-DAPym	4.9 ± 0.6	> 1000

<sup>1</sup> For each drug, the EC<sub>50</sub> value is the mean of the EC<sub>50</sub> of wild-type HBV that are shown in Tables 2 and 3.

<sup>2</sup> CC<sub>50</sub> are means values ± SD for 3 independent experiments performed in quadriplate.

**Table 2: Effect of selected anti-HBV drugs on the replication of wild-type HBV and HBV laboratory strains of genotype D carrying lamivudine (LAM)-, adefovir (ADV)- or lamivudine+adefovir (LAM+ADV)-resistance mutations.**

HBV strains	LAM <sup>b</sup>		ADV <sup>b</sup>		TDF <sup>b</sup>		ETV <sup>b</sup>		PMEO-DAPym	
	EC50 (μM)	FR <sup>a</sup>	EC50 (μM)	FR <sup>a</sup>	EC50 (μM)	FR <sup>a</sup>	EC50 (μM)	FR <sup>a</sup>	EC50 <sup>c</sup> (μM)	FR <sup>a</sup>
Wild-type	2.48 ± 0.67	1	15.8 ± 1.9	1	10.3 ± 1.3	1	0.8 ± 0.1	1	4.0 ± 0.51	1
ADV-R	2.65 ± 0.52	1.06	50.3 ± 11	3.2	46 ± 6	4.5	0.7	0.88	4.5 ± 0.35	1.1
LAM-R	>100	> 40	15.5 ± 1.8	0.98	35.2 ± 5.1	3.4	5 ± 0.25	6.25	4.7 ± 1.12	1.2
LAM+ADV-R	>100	> 40	100 ± 20	6.3	45.5 ± 6.1	4.4	5 ± 0.7	6.25	5.7 ± 0.77	1.4

<sup>a</sup>: FR: Fold resistance = ( mutant EC<sub>50</sub> ) / ( wt EC<sub>50</sub> ).

<sup>b</sup>: Data previously reported in (3).

<sup>c</sup>: Values represent the mean of at least 3 independent experiments, each performed in triplicate. For each experiment, the drug-resistant HBV strains and their corresponding wt strain were treated simultaneously with the same range of drug concentrations (from 0 to 100 μM for PMEO-DAPym, lamivudine, adefovir and tenofovir; from 0 to 10 μM for entecavir), and all the samples were extracted and analysed by southern blotting in parallel.

Lamivudine-resistant (LAM-R) mutant: rtL180M/M204V; Adefovir-resistant (ADV-R) mutant: rtN236T; Lamivudine+adefovir- resistant mutant (LAM+ADV-R): rtL180M/M204V/N236T.

Table 3: Effect of selected anti-HBV drugs on the replication of HBV mutants derived from the viral quaspecies of chronically infected patients.

HBV strains	LAM		ADV		TDF		ETV		PMEO-DAPym	
	EC <sub>50</sub> (μM)	FR <sup>a</sup>	EC <sub>50</sub> (μM)	FR <sup>a</sup>	EC <sub>50</sub> (μM) <sup>c</sup>	FR <sup>a</sup>	EC <sub>50</sub> (μM) <sup>c</sup>	FR <sup>a</sup>	EC <sub>50</sub> (μM) <sup>c</sup>	FR <sup>a</sup>
wt 1	0.64±0.17 <sup>c</sup>	1	13.6±4.08 <sup>c</sup>	1	13.6±4	1	0.09±0.03	1	4.4 ± 0.5	1
wt 2	0.1±0.2 <sup>b</sup>	1	10 ± 3 <sup>b</sup>	1	25±7.1	1	0.06±0.01	1	5.6 ± 1.0	1
<b>LAM-R</b>										
rtL180M/M204V	>100 <sup>b</sup>	>1,000	15±6 <sup>b</sup>	1.5	27±10	1.1	10.5±2.2	175	5.3±0.88	0.9
rtL180M/A181V	80±9 <sup>b</sup>	800	27±16 <sup>b</sup>	2.7	36±13	1.4	1.5±0.6	28	27±10.3	4.8
rtV173L/L180M/M204V	>100 <sup>c</sup>	>156	9.8±2.5 <sup>c</sup>	0.7	16±5.8	1.2	3.7±1.4	43	4.1±0.4	0.9
<b>LAM+ADV-R</b>										
rtV173L/L180M/A181V	100±5 <sup>b</sup>	1,000	48±19 <sup>b</sup>	4.8	42±8.1	1.6	2.75±1.2	50	24±4.5	4.3
rtV173L/L180M/A181V/M204V	>100 <sup>b</sup>	>1,000	40±20 <sup>b</sup>	4.0	45±21.3	1.8	≥50±15.9	≥800	18±7.0	3.2
rtV173L/L180M/A181V/M204V/N236T	>100 <sup>b</sup>	>1,000	77±20 <sup>b</sup>	7.7	46±18.3	1.8	25.4±5.5	461	12±3.0	2.1
rtV173L/L180M/A181V/N236T	>100 <sup>b</sup>	>1,000	>100 <sup>b</sup>	> 10	28± 5.6	1.1	0.5±0.14	9.0	29 ± 5.3	5.1
<b>ETV-R</b>										
rtL180M/S202G/M204V	>100 <sup>c</sup>	>156	15±4.5 <sup>c</sup>	1.1	27±9.8	2	18±8.7	210	4.5 ± 0.9	1.0

<sup>a</sup>; FR: Fold resistance = ( mutant EC<sub>50</sub>)/( wt EC<sub>50</sub>). For mutants rtV173L/L180M/M204V and rtL180M/S202G/M204V, the corresponding wt strain is wt1 (genotype H) and

FR = (mutant EC<sub>50</sub>)/(wt1 EC<sub>50</sub>). For the other mutants, the corresponding wt strain is wt2 (genotype E) and FR = (mutant EC<sub>50</sub>)/(wt2 EC<sub>50</sub>).

<sup>b</sup>; Data previously reported in (24).

<sup>c</sup>; Values represent the mean of at least 3 independent experiments, each performed in triplicate. For each experiment, the drug-resistant HBV strains and their corresponding wt strain were treated simultaneously with the same range of drug concentrations (from 0 to 100 μM for PMEO-DAPym, lamivudine, adefovir and tenofovir; from 0 to 10 μM for entecavir), and all the samples were extracted and analysed by southern blotting in parallel.

Lamivudine: LAM; Adefovir: ADV; Tenofovir: TDF; Entecavir: ETV; Lamivudine-resistant: LAM-R; Lamivudine+adefovir-resistant: LAM+ADV-R; Entecavir-resistant: ETV-R.

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